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By A. Tonomura

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Electron holography has recently paved a new way for observing and measuring microscopic objects and fields that were previously inaccessible employing other techniques. Full use is made of the extremely short wavelength of electrons, enabling electron holography to have a great impact on fields ranging from basic science to industrial applications. This book will provide an overview of the present state of electron holography for scientists and engineers entering the field. The principles, techniques and applications which have already been developed, as well as those which are expected to arise in the near future, will be discussed. The strange and interesting nature of electron quantum interference has intrigued the author who has devoted most of his life to this field, and motivated him to write this book in the hope of raising interest in, and encouraging others to enter, the field.

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1. Introduction

Electron holography is an imaging technique that records the electron interference pattern of an object on film (hologram) and then reconstructs an optical image by illuminating the hologram with a laser beam. In this process, electron wave fronts are transformed into optical wave fronts. Images of microscopic objects and fields that are so small that they can be observed only by using an electron beam with an extremely short wavelength are enlarged and reconstructed on an optical bench. This allows versatile optical techniques to be applied to overcome the limitations of electron microscopes.

Holography is now widely known - not only by scientists but also by artists, philosophers, and the general public - as a kind of stereoscopic photography using a laser beam. Holography was, however, originally invented in 1949 by Dennis Gabor, as a way of breaking through the resolution limit of electron microscopes [1.1,2]. The resolution of electron microscopy is not determined by the fundamental limitation, the electron wavelength, but by the large aberrations of the objective lens. It is impossible to construct an aberration-free lens system by combining convex and concave lenses due to the lack of any practical concave lens. Gabor intended to optically compensate for the aberrations in the reconstruction stage of holography. The intrinsic value of holography was not fully recognized until 1962, when Leith and Upatnieks [1.3] reconstructed clear images by using a coherent laser beam. Similarly, practical applications of electron holography have been made possible by the development of a coherent field-emission electron beam [1.4]. With this beam, electron holography has made a remarkable step towards new and practical applications [1.5-13].

To take a concrete example, the phase distribution of the electron wave function transmitted through an object has become observable to within a measurement precision as high as $2\pi/100$, while in electron microscopy only the intensity distribution can be observed. This technique has enabled us to directly observe magnetic lines of force of a magnetic object: The contour fringes in the interference micrograph follow magnetic lines in $h/e \approx (4\times10^{-15} \text{Wb})$ units. This was applied to actual problems such as the magnetic-domain structure of a ferromagnetic thin film and also the observation of magnetic fluxons penetrating a superconductor.
2. Principles of Holography

Holography, a unique imaging technique that does not use lenses, is only based on the most fundamental properties of waves, interference and diffraction. Holography is therefore applicable to all kinds of waves - light, X-ray, sound, electron, or neutron waves - regardless of whether there is a lens for the wave. A major feature of holography is that a complete wave (i.e., a complex amplitude) can be reconstructed from an exposed film called a hologram (a photograph containing all information). For this reason, laser holography can produce a far more realistic stereoscopic image than can be provided by any other technique.

The first step in holography consists of recording an interference pattern, or hologram, between the reference wave $\phi_r$ and the wave $\phi_0$ scattered from an object. Here, $\phi_0$ and $\phi_r$ represent the complex amplitudes of these waves. Since these two waves are partial waves emitted from a common source, they are coherently superposed at the hologram plane to interfere with each other. The intensity $I$ of the interference pattern is given by

$$I = |\phi_0 + \phi_r|^2. \quad (2.1)$$

When the interference pattern is exposed onto a film and developed, the amplitude transmittance $t$ of the film is given by

$$t = I^{-\gamma/2} = |\phi_0 + \phi_r|^{-\gamma}, \quad (2.2)$$

where $\gamma$ indicates the contrast value of the film. If the film is reversed and the contrast is inverted to make $\gamma = -2$, $t$ becomes proportional to $I$, though this condition is not always necessary for image reconstruction.

The second step in holography consists of reconstructing the image of the original object. For simplicity, the hologram is illuminated with the same reference wave as that used in forming the hologram. The transmitted amplitude $T$ is then given by

$$T = |\phi_0 + \phi_r|^2 \phi_r = (|\phi_0|^2 + |\phi_r|^2)\phi_r + |\phi_r|^2 \phi_0 + \phi_0^* \phi_r^2. \quad (2.3)$$

The imaging properties of holography can be understood simply by interpreting the terms in this equation. The first term corresponds to the transmitted wave, and the second term corresponds to the wave scattered from the object. This means that an exact image can be reconstructed if the second term can be observed independently of the others. The third
term is similar to the second one, but its phase value is opposite in sign. This term produces a conjugate image, the amplitude of which is the complex-conjugate of the reconstructed image.

The image formation is essentially the same, even when the hologram is illuminated with a wave whose wavelength differs from that of the original reference wave. Parameters such as the image magnification and the distance between the hologram and the image depend on the ratio of the two wavelengths. This will be discussed in more detail later. Up to this point, holographic image formation seems to work perfectly, but this is not the case when higher-order terms are taken into consideration. The aberrations associated with this type of imaging are similar to those for imaging with an optical lens [2.1].

2.1 In-Line Holography

The simplest way of producing a hologram is illustrated in Fig. 2.1a which shows a point object illuminated with a plane wave. The transmitted plane wave plays here the role of a reference wave. This type of holography is called in-line holography because the object and reference waves propagate along a line. The amplitudes of these reference and object waves can be expressed as

\[ \phi_r = e^{ikx} \quad \text{and} \quad \phi_o = i \frac{f}{r} e^{-ikr}, \]

where \( f \) is the scattering amplitude from the point object. Then the intensity distribution \( I(x, y) \) on the hologram plane at a distance \( l \) from the object is given by

\[ I(x, y) = |\phi_0 + \phi_r|^2 \approx 1 + \left( \frac{f}{l} \right)^2 - \frac{2f}{l} \sin \left( \frac{k(x^2 + y^2)}{2l} \right), \]

if \( l^2 \gg x^2 + y^2 \) and consequently \( r = \sqrt{l^2 + x^2 + y^2} \approx l + (x^2 + y^2)/(2l) \). The interference pattern given by (2.5) consists of concentric fringes and is called a zone plate.

If this hologram is recorded on film with a contrast of \( \gamma = -2 \) and is then illuminated with a plane wave identical to the reference wave, it is possible to express the resultant transmitted amplitude \( T(x, y) \) as

\[ T(x, y) = e^{ikx} \left[ 1 + \left( \frac{f}{l} \right)^2 + i \frac{f}{l} \exp \left( \frac{ik(x^2 + y^2)}{2l} \right) - i \frac{f}{l} \exp \left( -\frac{ik(x^2 + y^2)}{2l} \right) \right]. \]

(2.6)
Fig. 2.1. In-line holography of a point object: (a) Hologram formation, and (b) image reconstruction.

The first and second terms here represent the transmitted plane waves. The third term gives the original wave scattered from the point object, that is, a spherical wave diverging from point O (Fig. 2.1b). The fourth term represents a spherical wave converging to the point O', located at the position mirror-symmetric to the point O with respect to the hologram plane. This fourth term describes the conjugate image.
In short, the hologram of a point object, of which the hologram is a zone plate, plays dual roles of concave and convex lenses with the same focal length \( f \). Illuminating this hologram with a plane wave therefore produces both divergent and convergent spherical waves.

We can now discuss the resolution of the reconstructed image. An in-line hologram acts as a lens, and a point image is formed by the interference of all the waves diffracted from the zone-plate fringes. The image resolution \( d \) is therefore determined essentially by the diameter \( D \) of the zone plate, which corresponds to the diameter of the lens aperture, i.e.,

\[
d = 1.6 \frac{\lambda}{D} f.
\] (2.7)

This value of \( d \) is equal to the shortest fringe spacing at the outermost fringe of the zone plate.

Generally, it is not possible to observe only the reconstructed image: the defocused pattern of the conjugate image is inevitably superimposed onto the reconstructed image. This results from the fact that the two images both lie on the same axis. The problem of separating the twin images was a persistent obstacle to holography. A solution was found, however, by introducing a new method called off-axis holography [2.2]. With this method, a reference wave is tilted with respect to an object wave. Further details will be provided in Sect.2.2 on off-axis holography.

Although off-axis holography could solve the problem of a conjugate image, further efforts were made to reconstruct in-line holographic images free from disturbances. The most effective of these methods is Fraunhofer in-line holography. With this approach, in-line holograms are formed in the Fraunhofer diffraction plane of an object, that is, under the condition

\[
a^2 \ll \lambda f,
\] (2.8)

![Fig.2.2. Fraunhofer in-line holography. When a hologram is formed in the Fraunhofer diffraction region of an object (2.8), the reconstructed image is not disturbed by the conjugate image. The dimensions are reduced to those in the hologram-formation process](image)